Improvement of the Cloud Physics Formulation in the U.S. Navy Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)

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Grant Number: N00014-03-1-0304
http://www.cimms.ou.edu/

LONG-TERM GOALS

Correct representation of cloud processes is critical in producing accurate numerical weather prediction (NWP) forecasts. The major goal of the project is to develop state of the art parameterizations of cloud processes and implement them into COAMPS.

OBJECTIVES

To improve representation of cloud microphysical processes in mesoscale models, we are developing parameterizations of giant aerosols, inhomogeneous radiative transfer, as well as parameterizations of rain rates and radar reflectivity. We are expanding our efforts to generalize these and other cloud physics parameterizations for cumuliform clouds.

APPROACH

Large eddy simulation (LES) with size resolving microphysics represents the full interaction of 3D dynamics and microphysics. We apply this powerful model to develop parameterizations of various physical processes. Our previous work demonstrated the importance of including giant CCN (GCCN) with radii greater than 1 μm. We have developed a GCCN parameterization for use in mesoscale models and evaluated its the sensitivity of cloud microphysical and dynamical parameters to changes in GCCN and background sulfate CCN concentration.

In an effort to generalize our approach in the development of microphysical parameterizations, we are exploring microphysical feedbacks and parameterizations in warm rain cumuliform clouds. In order to accomplish this, we have expended significant effort to rewrite our LES model to run on distributed parallel computing architectures. Being able to take advantage of significant computational resources at our disposal, we are now able both to resolve both fine scale mechanisms (stratocumulus entrainment, lateral entrainment in cumulus) and run on large enough domains to represent the mesoscale component of the circulation.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2007	**Annual**	**00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE
Improvement Of The Cloud Physics Formulation In The U.S. Navy Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Oklahoma,Cooperative Institute for Mesoscale Meteorological Studies,120 David L. Boren Blvd., Suite 2100,Norman,OK,73072-7304

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
Correct representation of cloud processes is critical in producing accurate numerical weather prediction (NWP) forecasts. The major goal of the project is to develop state of the art parameterizations of cloud processes and implement them into COAMPS.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Finally, recently a number of new parameterization have been developed using synthetic datasets created by solving coagulation equation under a variety of input conditions. We have explored the dependence of parameterization on dataset, emphasizing the importance of dynamically balanced datasets created by the 3D LES model.

WORK COMPLETED

The following tasks have been completed:

1. Development of a parameterization of the effects of giant CCN for bulk microphysical models. A paper describing the parameterization has been accepted at the Journal of Atmospheric Sciences.

2. Evaluating the fidelity of 1D radiation parameterizations by comparison with an inhomogeneous 3D radiative transfer scheme. We demonstrated that the 1D parameterization is quite accurate for both solid stratocumulus and broken fields of trade cumulus.

3. Dynamics and microphysics of continental stratus have been simulated by the CIMMS LES and found to be in good agreement with radar-derived Doppler velocities.

4. Development of a new parameterization for rain rate and radar reflectivity for use in marine stratocumulus. The parameterization can be easily linked to the prognostic variables used in two-moment microphysical parameterizations.

5. Formulation of a new methodology for the development of microphysical parameterizations based on dynamically balanced datasets obtained from LES simulations.

RESULTS

1. Parameterization of giant CCN in NWP models

The addition of giant CCN (GCCN) to stratocumulus can have pronounced impacts both on precipitation development and also on cloud dynamical properties. Here we summarize how GCCN affect cloud and dynamical properties, which can have impact for short-term forecasting applications. The formulation, testing, and sensitivity of the GCCN parameterization are reported in a paper accepted to the Journal of Atmospheric Sciences.

The effect on cloud and dynamical properties of adding giant CCN to background clean and polluted environments was evaluated in a large eddy simulation framework using the new CIMMS GCCN parameterization. Adding GCCN to a clean CCN background has little effect on cloud parameters such as drizzle rate and cloud-mean droplet concentration, largely because the clouds are already drizzling. Additional GCCN, however, tend to make them drizzle even more, leading to a slight reduction in LWP. Higher concentrations of GCCN, however, have no effect on the mean turbulent intensity of boundary layer eddies, as measured by the vertical velocity variance.

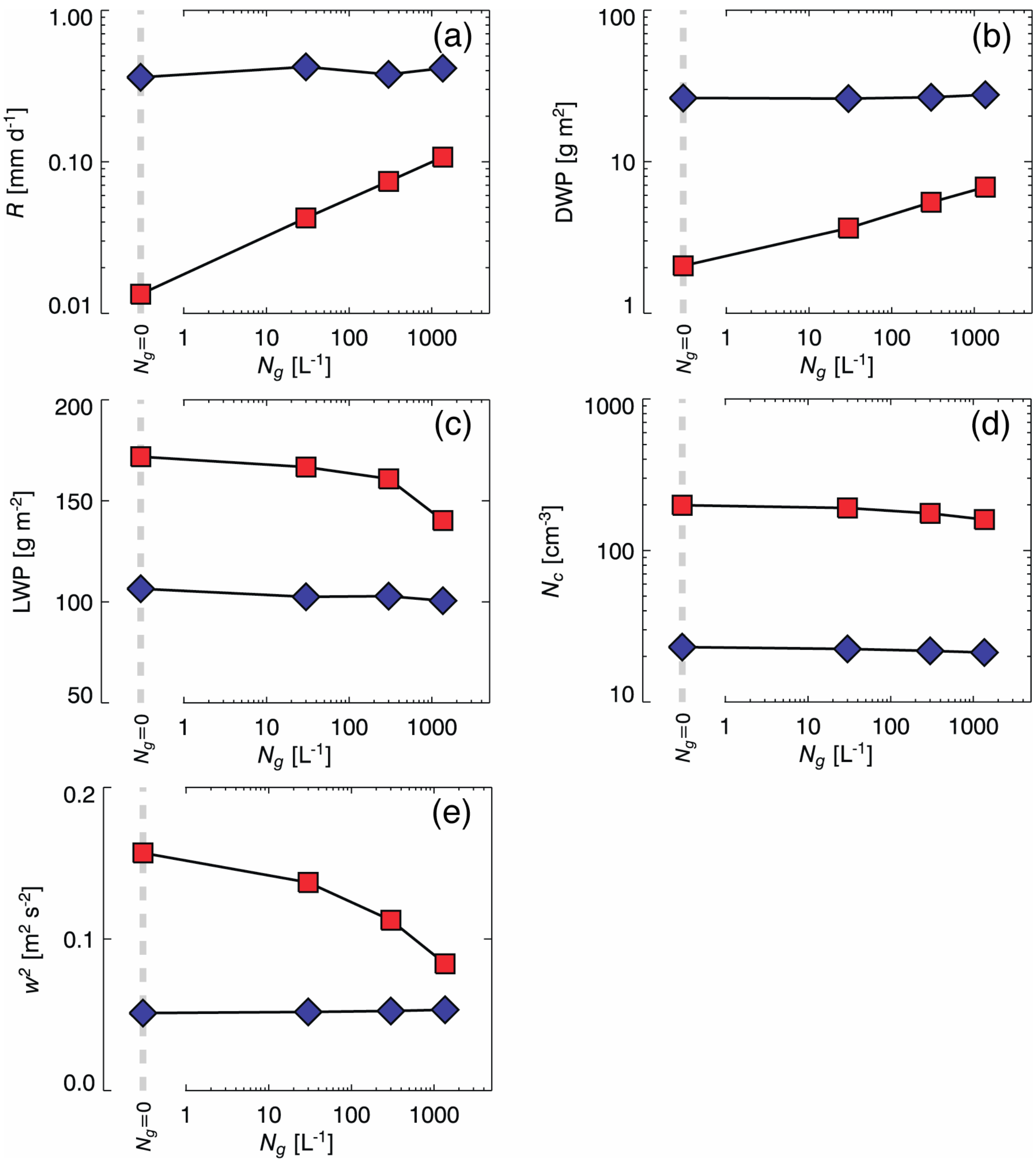

Figure 1. Mean (4-6 h) boundary layer quantities as a function of GCCN concentration for polluted (red squares) and clean (blue diamonds) background CCN conditions. (a) Surface drizzle rate; (b) Drizzle water path; (c) Liquid water path; (d) Mean droplet concentration over the cloud layer; (e) Vertical velocity variance averaged over the boundary layer. [graph: Giant CCNs significantly affect cloud and boundary layer dynamical parameters in the polluted marine environment]

Adding GCCN to a polluted CCN background results in a noticeable increase in drizzle content and rate, with higher drizzle rates associated with depleted cloud LWP values. Droplet concentration decreases with increasing GCCN amounts, though this effect is masked somewhat by the logarithmic axis employed. Vertical velocity variance decreases significantly with increasing GCCN, a result in this particular case of the stabilizing effect of drizzle. For higher values of GCCN, the mean variance decreases and the vertical profile tends to take on more of a decoupled shape.

The GCCN parameterization is best implemented as a boundary value problem, with either a constant GCCN value or flux at the surface. This formulation is consistent with the physical source for GCCN (sea spray) and avoids an unphysical burst of precipitation and rapid depletion of GCCN that occurs when configured as an initial value problem. The boundary value problem couples naturally to wind speed-dependent parameterizations of sea salt flux from the ocean surface. In the boundary value formulation, with the only source of GCCN coming from the surface, after a short time GCCN profiles over the subcloud layer attain steady state, indicating that GCCN processing by the cloud is in approximate balance with the surface source.

2. Parameterizations of multi-dimensional radiative effects in low altitude clouds — are current 1D methods sufficiently accurate?

Numerical models ranging from global climate models (GCMs) down to large eddy simulation (LES) models nearly universally employ one-dimensional treatments of radiative transfer (RT).. However, 1D RT neglects horizontal photon transport and associated effects such as cloud shadowing and radiative cooling of cloud lateral boundaries, which may be important for situations of complex cloud geometry and internal cloud structure. Recent comparisons of multi-dimensional (MD) RT codes have demonstrated that atmospheric radiative transfer is fundamentally multi-dimensional and that employing IPA methods in numerical models may introduce systematic biases into a model solution.

In order to evaluate the importance of MD radiative effects on cloud structure and dynamics, we have adopted a large eddy simulation (LES) framework employing MD radiative transfer (Spherical Harmonics Discrete Ordinate Method — SHDOM). Our simulations address how MD effects interact directly with the model cloud and dynamical fields, as opposed to indirectly through, for example, modifying the surface radiative flux and energy balance. Simulations employing longwave MD and IPA radiative transfer are performed for cases of unbroken, marine boundary layer stratocumulus and a broken field of trade cumulus. “Snapshot” calculations of MD and IPA radiative transfer applied to LES cloud fields indicate that the total radiative forcing changes only slightly, although the MD effect significantly modifies the spatial structure of the radiative forcing. Simulations of each cloud type employing MD and IPA radiative transfer, however, differ little. Snapshot calculations of the broken cloud case suggest a slight increase in radiative cooling, though few systematic differences are noted in the interactive simulations. For the solid cloud case, relative to using IPA, the MD simulation exhibits a barely detectable reduction in entrainment rate and boundary layer TKE relative to the IPA simulation. This reduction is consistent with both the slight decrease in net radiative forcing and a negative correlation between local vertical velocity and radiative forcing, which implies a damping of boundary layer eddies.

We have two explanations for the insensitivity of the cloud properties to MD effects. For the solid ASTEX cloud, parcels traversing the region of cooling at cloud top pass through areas of greater forcing, as well as regions of less. Thus, the parcel forcing tends to be insensitive to changes in the spatial forcing distribution. For the broken BOMEX cloud case, the radiative cooling is a relatively minor contribution to the total energetics, and the subtle MD effects are only a small percentage of that. Our results (submitted for publication in Journal of the Atmospheric Sciences) indicate that 1D parameterizations sufficiently represent longwave radiative transfer for low altitude clouds.

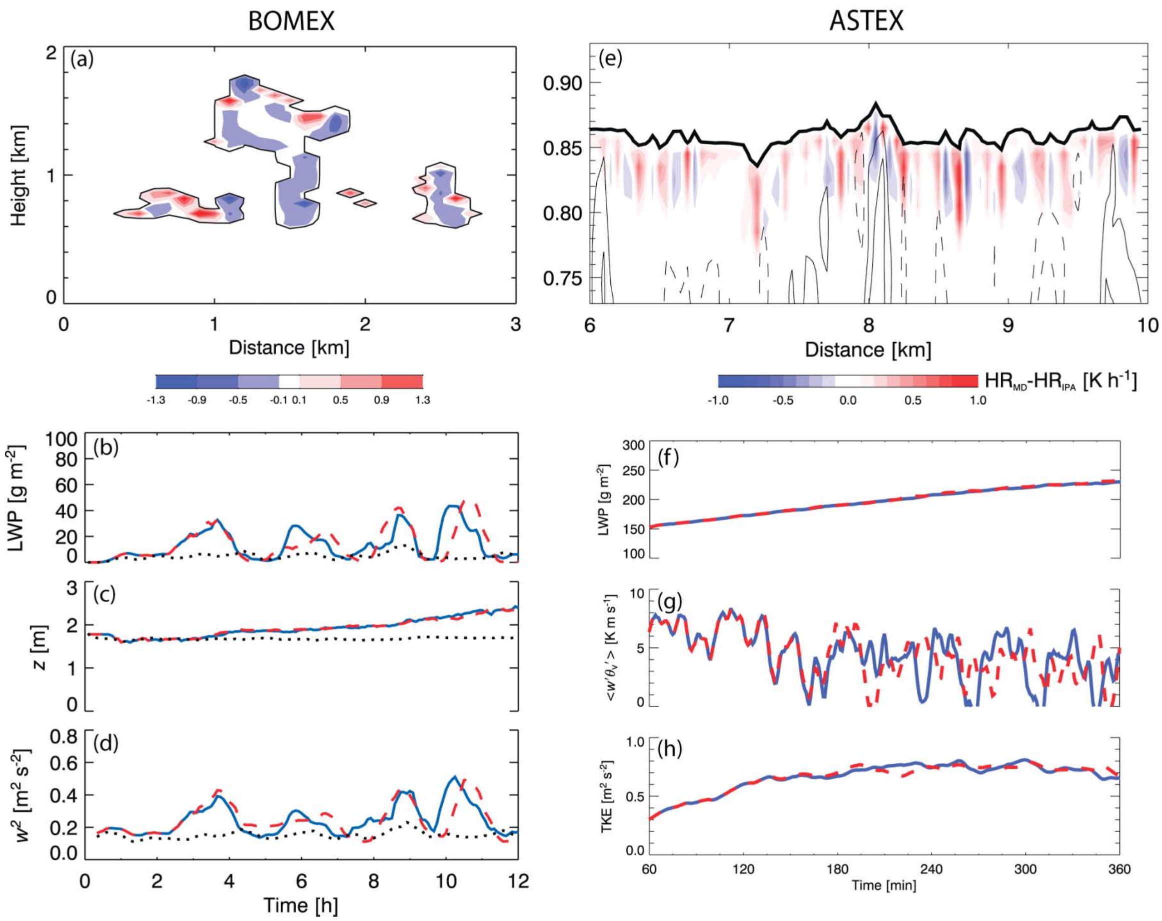

Figure 2. The effects of multi-dimensional radiative transfer on cloud system evolution. (a) Difference in radiative forcing between MD and 1D longwave radiative transfer for a typical trade cumulus cloud. (b)-(d) Evolution of LWP, inversion height, and vertical velocity variance for the BOMEX simulations. The blue (red) line represents the MD (1D) simulation. The black dotted line corresponds to a simulation with no radiative forcing. (e) As in (a) but for the top 100 m of the solid stratocumulus cloud in the ASTEX case. (f)-(h) Evolution of LWP, buoyancy flux, and TKE for the ASTEX simulations. [graph: 1D radiative parameterization in Sc and shallow Cu quite accurately predicts overall cloud parameters]

3. Dynamics and microphysics of continental stratus

The classical studies of low cloud systems focused on stratocumulus and trade cumulus in marine environments. Midlatitude low clouds are also present over inland coastal regions and the continental interior, and are frequently associated with the passage of synoptic waves. These low clouds that usually form in the subsidence region behind the cold front bear significant structural resemblance to marine stratocumulus.

Studies employing continuous years of low cloud observations over the southern great plains ARM Climate Research Facility (ACRF) emphasized their climatological, microphysical, and radiative characteristics. Recent millimeter-wave cloud radar observations, specifically those with a high sampling rate of the boundary layer, are ideal for exploring the dynamic aspects of these cloud systems. These upgraded sensors enable "large eddy observations" (LEOs; Kollias and Albrecht, JAS 2000) — the coherent sampling of boundary layer turbulence structures responsible for most of the transport. High resolution cloud radar observations (95 GHz W-band ARM Cloud Radar -- WACR) and the new CIMMS large eddy simulation with size-resolving microphysics (System for Atmospheric Modeling -- Explicit Microphysics (SAMEX)) were employed to analyze the cloud structure and turbulent quantities for a typical springtime postfrontal boundary layer stratocumulus case.

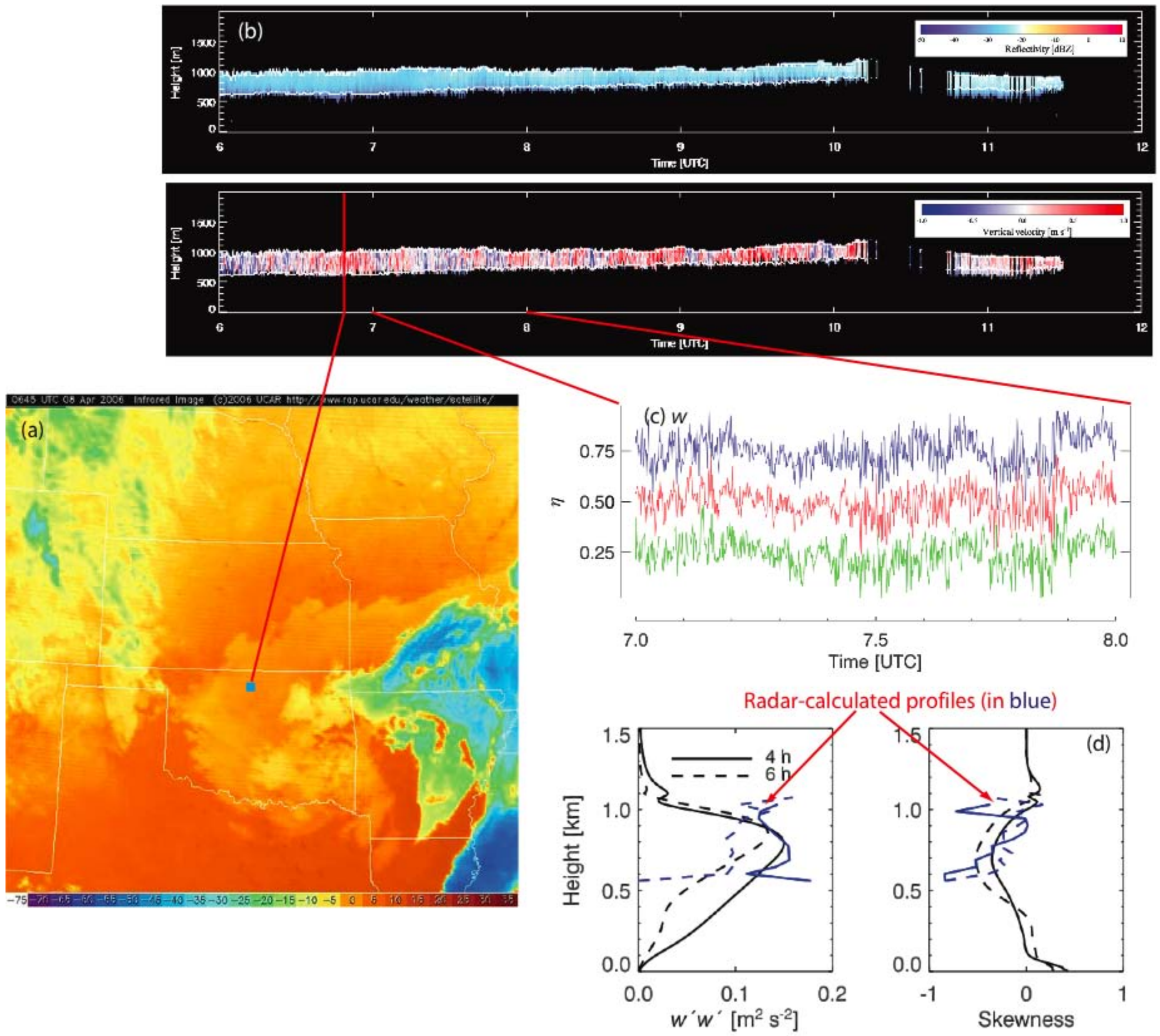

Figure 3. Characterization of stratocumulus associated with a midlatitude synoptic system passing over the southern great plains ACRF. (a) GOES IR imagery from 0645 UTC 8 April 2006. Blue box indicates location of the ACRF; (b) Processed radar reflectivity and velocity data from the WACR; (c) Vertical velocity at three levels in the cloud corresponding to a nondimensional cloud-normalized height. The graphical distance between 0.50-0.75 corresponds to 1 m s^{-1}; (d) Variance and skewness calculated from a large eddy simulation of this case. Statistics calculated from the WACR data are overlaid on the LES profiles. [graph: LES model simulations of continental stratocumulus are in good agreement with radar derived velocity variance and skewness]

Preliminary observational and modeling analyses suggest both similarities and differences relative to marine stratocumulus. For clouds containing little or no precipitation, boundary layer turbulence structures sampled by the WACR are coherent in both time and in the vertical. Statistics from the WACR indicate a slightly subadiabatic cloud layer and an eddy structure dominated by updrafts and downdrafts of roughly similar properties. The slight negative skewness implies that convection driven top-down by cloud top longwave cooling weakly predominates. The overall magnitude of in-cloud and turbulence was relatively weak, compared to typical marine cases. The LES captures the magnitude of in-cloud turbulence and skewness present in the WACR observations, which suggests that the model represents the overall character of the flow reasonably. Relative to marine clouds, which are typically studied in a Lagrangian framework with relatively weak advective forcings, continental clouds associated with synoptic systems require highly constrained estimates of these advective terms. These results from LEO and LES constitute a robust test case of observationally constrained microphysical and dynamical parameters, which may be used to determine whether mesoscale model boundary layer and turbulence parameterizations, tuned to perform best on marine stratocumulus, perform adequately when applied to continental low clouds.

4. Parameterization of drizzle flux and radar reflectivity in marine stratocumulus clouds

The development of cloud physics parameterizations and remote sensing microphysical retrievals rely heavily on the knowledge of the shape of drop size distributions (DSDs). Many investigations assume that DSDs in the whole, or parts of the drop size range, may be approximated by known analytical functions. The most frequently employed approximations are gamma, lognormal, Khrgian-Mazin, and Marshall-Palmer type functions. At present, little is known about the accuracy of each of these approximations, especially their ability to successfully represent higher moments of the DSD.

We evaluated the accuracy of DSD approximations in stratocumulus and shallow convective clouds using a combination of lognormal and gamma-type functions. The DSDs are generated using the latest version of the CIMMS LES explicit microphysics model (SAMEX) in simulations of cases observed during the ASTEX, DYCOMS-II and RICO field projects. Special emphasis in the analysis is placed on the fidelity of representing the higher moments of the drop spectra, such as precipitation flux and radar reflectivity.

Our results indicate that approximating drop spectra in drizzling stratocumulus by Gamma-type distributions proves to be much more accurate than approximation by the lognormal distribution. In numerical models which use two-moment microphysical parameterization schemes, the six parameters defining the two-mode Gamma distribution can be expressed through the four predictive microphysical variables describing concentrations and mixing ratios of cloud and rain drops. The remaining two parameters can be expressed by parameterizing the cloud and drizzle mode drop spectra dispersion. Our results show that the drizzle mode dispersion can be successfully parameterized as a function of either drizzle drop concentration alone, or as a function of drizzle drop concentration and drizzle mixing ratio (Figure 4, middle and bottom panels).

It has to be noted that recently three-moment cloud physics parameterizations have been developed (Milbrandt and Yau, 2005) and implemented, e.g., in the ARPS model (Ming Xue, personal communication). In this case the Gamma distribution can be very accurately expressed through three parameters and even more accurate parameterizations of rain rate and radar reflectivity can be obtained (Figure 4, top panels).

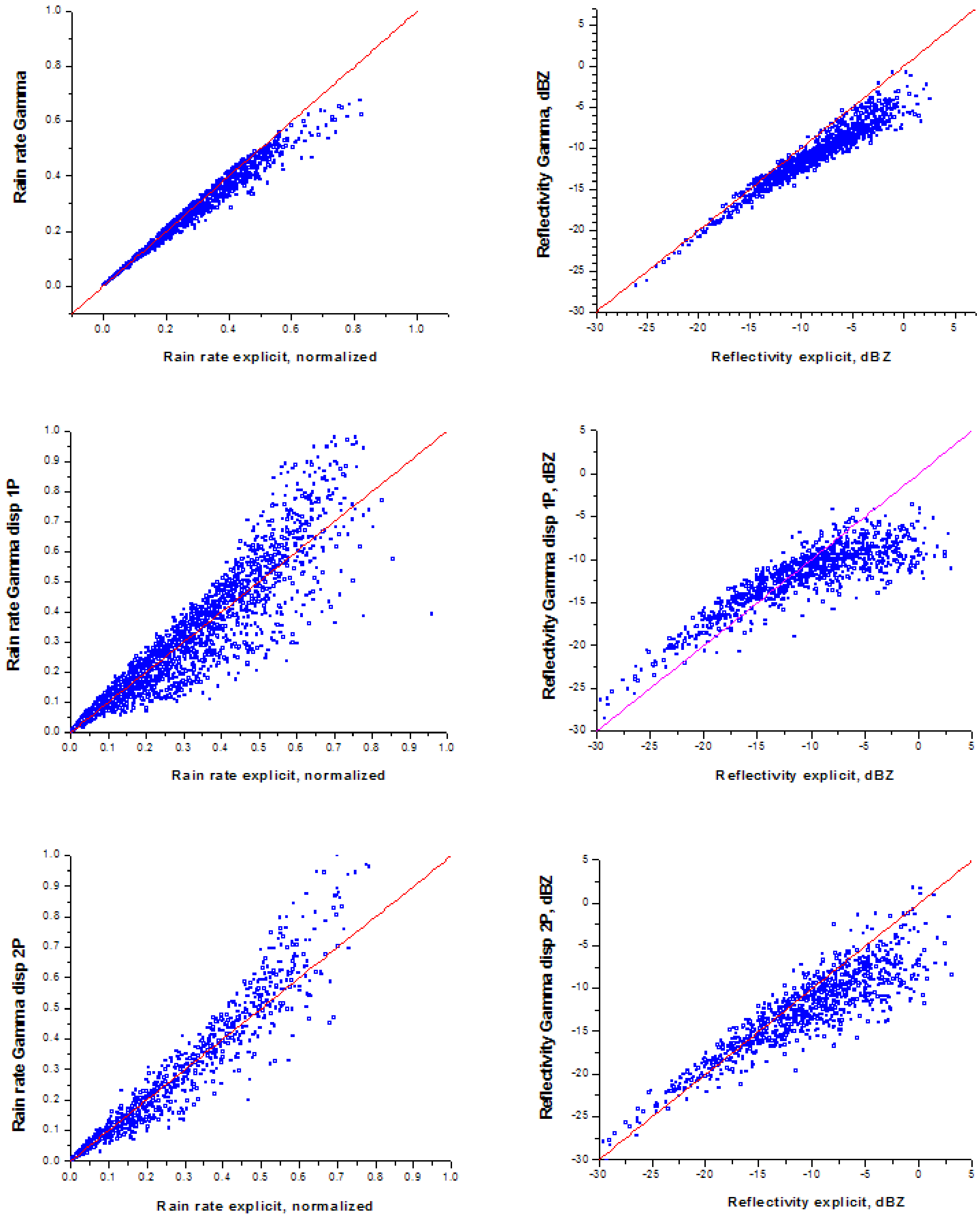

Figure 4. Comparions of rain rates (left panels) and radar reflectivity (right) approximated by two-mode Gamma-type distributions. Top row: Gamma-distribution identifined by 3 parameters. Middle row: Gamma-distribution defined by 2 parameters with dispersion approximated by a function of drizzle concentration. Bottom row: The dispersion is approximated as a function of drizzle concentration and drizzle mixing ratio. [graph: rain rates and radar reflectivity can be parameterized reasonably well in the two moment cloud physics scheme. The use of the three moment scheme provides the most accurate parameterization]

5. The role of dynamically balanced dataset in cloud microphysics parameterization development

A number of cloud microphysical parameterizations have been developed during the last decade using various datasets of cloud drop spectra. These datasets can be obtained either from observations, artificially produced by some drop size spectra generator (e.g. by solving the coagulation equation under different input conditions), or obtained as output of LES model which can predict cloud drop spectra explicitly. Each of the methods has its deficiencies, for example in-situ aircraft observations being constrained to the flight path and the dependence of coagulation equation solutions on input conditions. The ultimate aim is to create a cloud drop spectra dataset that mimics realistically drop parameters in real clouds. These parameters are closely related to the distribution of thermodynamical conditions, which are difficult, if not impossible, to obtain a priori.

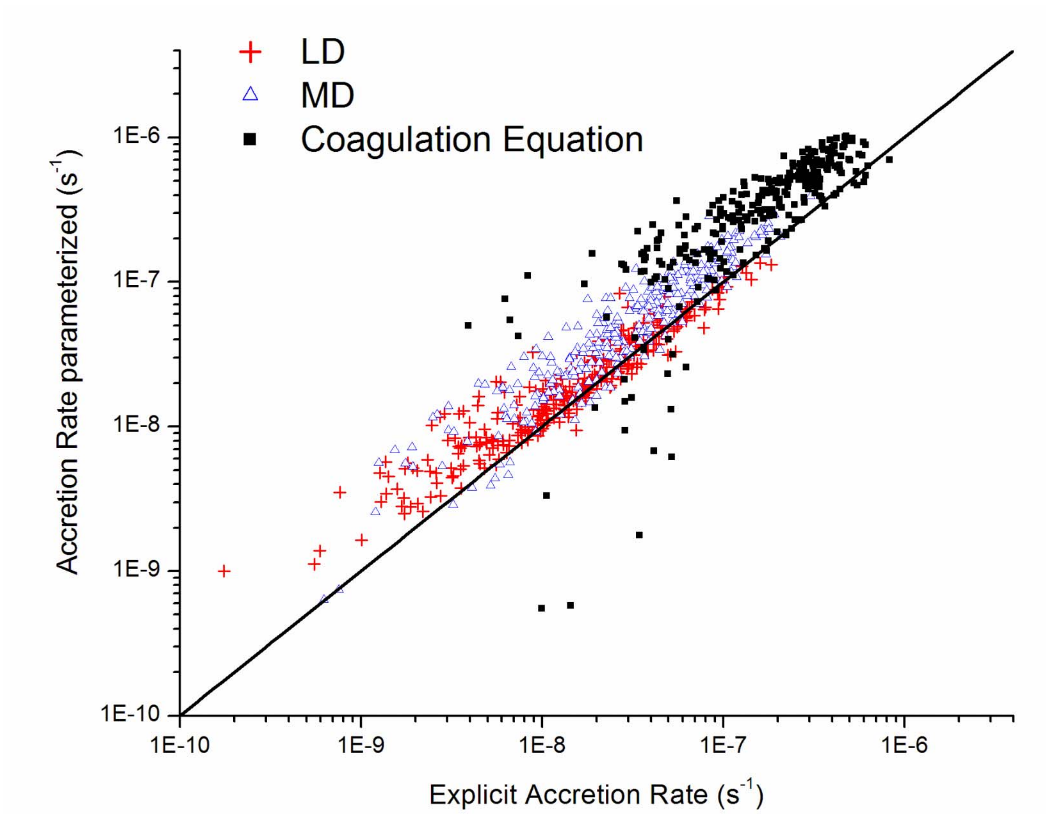

Figure 5. The comparison of parameterized vs. explicit accretion rates obtained from three different datasets. Crosses denote the dataset from simulation in light drizzling (LD) stratocumulus, triangles represent the dataset with moderate drizzle (MD), and squares represent dataset obtained from the solutions of the coagulation equation. [graph: the dynamically unbalanced dataset created by solutions to the coagulation equation results in significant parameterization errors]

The best tool to create a dynamically balanced dataset is an LES model with explicit microphysics, since it is able to provide a full range of drop spectra generated by realistically represented turbulence. We explored the effects of dataset selection on cloud microphysical parameterization by simulating several cases of stratocumulus clouds observed during the Atlantic Stratocumulus Transition

Experiment (ASTEX) field experiment in clean and polluted air masses. The simulated cloud layers represented cases with light (LD), moderate (MD) and heavy (HD) intensities of drizzle in the cloud. The results of the study showed high sensitivity of the derived parameterization on the choice of dataset (Figure 5). We emphasize that the development of accurate parameterizations should require the use of dynamically balanced cloud drop spectra datasets.

IMPACT/APPLICATIONS

Improved parameterization of cloud physical processes will result in more accurate numerical weather prediction for U.S. Navy operations. Current results are relevant to providing more accurate forecasts of cloud and radiative parameters.

TRANSITIONS

Future improvements to the COAMPS cloud physics parameterization package (activation parameterization, giant CCN parameterization) developed at CIMMS/OU will be made available to NRL and registered COAMPS users at large. Our results have been disseminated to the science community at five conferences and by publication in three major refereed journals and conference proceedings (total of 10 papers).

RELATED PROJECTS

We are using our participation in the GCSS (GEWEX Cloud Systems Study) RICO (Rain in Cumulus over the Ocean) study to generalize these techniques to more cumuliform low cloud systems. Our participation in the ARM program greatly enhances the verification component of our work detailed in subsection 3 of the Results.

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